REPORT DOCUMENTATION PAGE	*Form Approved* *OMB No. 0704-0188*

1. REPORT DATE *(DD-MM-YYYY)*	**2. REPORT TYPE**	**3. DATES COVERED** *(From - To)*
17-09-2015	Final	30 May 2014 to 29 May 2015

4. TITLE AND SUBTITLE Nonlinear dynamics of photonics for optical signal processing - optical frequency conversion and optical DSB-to-SSB conversion	**5a. CONTRACT NUMBER** FA2386-14-1-0006 **5b. GRANT NUMBER** Grant 134113 **5c. PROGRAM ELEMENT NUMBER** 61102F
6. AUTHOR(S) Prof. Sheng-Kwang Hwang	**5d. PROJECT NUMBER** **5e. TASK NUMBER** **5f. WORK UNIT NUMBER**
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) National Cheng Kung University 1 University Rd Tainan Taiwan	**8. PERFORMING ORGANIZATION REPORT NUMBER** N/A
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) AOARD UNIT 45002 APO AP 96338-5002	**10. SPONSOR/MONITOR'S ACRONYM(S)** AFRL/AFOSR/IOA(AOARD) **11. SPONSOR/MONITOR'S REPORT NUMBER(S)** 134113

12. DISTRIBUTION/AVAILABILITY STATEMENT

Distribution Code A: Approved for public release, distribution is unlimited.

13. SUPPLEMENTARY NOTES

14. ABSTRACT

The objective is to study nonlinear dynamics of semiconductor lasers for certain optical signal processing functionalities, including optical DSB-to-SSB conversion, photonic microwave generation and stabilization, and photonic microwave amplification.

15. SUBJECT TERMS

Non-linear Dynamics, Add-drop Multiplexing, Optical Amplifier, Terahertz Electronics, Four-wave mixing, Radio-over-fiber networks, Intensity-asymmetry

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			Seng Hong, Ph.D.
U	U	U	SAR	13	**19b. TELEPHONE NUMBER** *(Include area code)* +81-42-511-2000

Standard Form 298 (Rev. 8/98)
Prescribed by ANSI Std. Z39.18

Final Report for AOARD Grant FA2386-14-1-0006

Project Title

Nonlinear dynamics of photonics for optical signal processing – optical frequency conversion and optical DSB-to-SSB conversion

Performance Period

May 30, 2014 ~ May 29, 2015

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Abstract

In this project, we have studied nonlinear dynamics of semiconductor lasers for certain optical signal processing functionalities, including optical DSB-to-SSB conversion, photonic microwave generation and stabilization, and photonic microwave amplification. For the optical DSB-to-SSB conversion, we have demonstrated that, for operating microwave frequencies up to 40 GHz, our proposed scheme can regenerate the microwave features, such as linewidth and phase noise, of an optical DSB input while converting its optical feature into SSB with an intensity difference of at least 20 dB. The bit-error ratio down to 10^{-9} for a data rate of at least 2.5 Gb/s is feasible with a receiver sensitivity improvement of up to 15 dB. Such conversion is feasible for an operating microwave frequency up to at least 100 GHz, which has not yet been experimentally demonstrated due to the bandwidth limitation of the electronics used in our study, not by our proposed scheme. The proposed system can be self-adapted to certain changes in the operating microwave frequency and can operate stably under certain fluctuations in the input optical power and frequency. For the photonic microwave generation and stabilization, we have demonstrated that broadly tunable, from 10 to 40 GHz, and highly stable, a linewidth down to 1 Hz, microwaves can be generated "photonically" using our proposed scheme. A higher frequency, such as 100 GHz or more, is feasible, which has not yet been experimentally demonstrated due to the bandwidth limitation of the electronics used in our study, not by

our proposed scheme. Compared to other photonic schemes proposed in the literature, such as mode-locked lasers, optoelectronic oscillators, and laser optical heterodyne, our scheme is (1) up to 100 times better in terms of frequency tunability, (2) up to 1000 times better in terms of microwave linewidth and stability, or (3) much simpler in terms of system structure and operation. For the photonic microwave amplification, we have demonstrated that microwaves can be amplified "photonically" by up to 30 dB for a broad frequency range from 10 to 60 GHz. A higher frequency, such as 100 GHz or more, is feasible, which has not yet been experimentally demonstrated due to the bandwidth limitation of the electronics used in our study, not by our proposed scheme. Compared to other photonic schemes proposed in the literature, such as passive optical filtering and Brillouin scattering, our scheme is (1) more than 100 times better in terms of frequency tenability, (2) more than 100 times better in terms of microwave gain, and (3) much simpler in terms of system structure and operation. These signal processing functionalities are either expensive or difficult, if not impossible, to achieve using traditional electronic approaches if high-frequency, such as V and W bands, applications are of interest. Therefore, our proposed photonic schemes provide promising and attractive solutions for various applications in, for example, (1) wireless communication of the 5th-generation or beyond requiring microwaves ranging from 30 GHz to more than 100 GHz, (2) optical signal processing for optical communications requiring microwaves ranging from 10 GHz to 160 GHz, and (3) phase-array antennas for commercial, academic, and military purposes delivering microwaves through fibers to remote areas for wireless sensing, imaging, and detection.

Introduction

Radio-over-fiber has recently attracted great attention due to the strong demand in distributing microwave subcarriers over long distances through fibers for antenna remoting applications, such as phase-arrayed radars and broadband wireless access networks. Such radio-over-fiber systems adopt an architecture where microwave subcarriers are generated in the optical domain at a central office and next transmitted to remote base stations through fibers. Microwave subcarriers are converted to the electrical domain at the base stations using photodetectors, which are next radiated by antennas over small areas. Certain characteristics of the microwave-modulated optical carriers are necessary in order to simultaneously satisfy the requirements in both the optical domain and the electrical domain, such as high microwave frequency, low microwave phase noise, optical single-sideband (SSB) modulation, and high optical modulation depth. A variety of different schemes have therefore been proposed to simultaneously achieve these photonic microwave characteristics. In this project, we have studied nonlinear dynamics of photonics for optical DSB-to-SSB conversion, photonic microwave generation and stabilization, and photonic microwave amplification. In particular, we have focused on

studying period-one nonlinear dynamics in a photonic active device, namely semiconductor laser, for such processing purposes. Some highlights of our research are briefly presented as follows.

Approach

When a photonic active device, such as semiconductor laser in the present study, is subject to external optical injection, as shown in Fig. 1 (left), different nonlinear dynamical states could be excited, including period-one dynamics and deterministic chaos. When such a photonic system is operated under period-one dynamics, the optical spectrum of the system output consists of multiple spectral components, as shown in Fig. 1 (right), one at the frequency of the injection and others at frequencies equally separated away from the injection frequency. The frequency separation between spectral components is referred to as the period-one oscillation frequency, which can be easily adjusted by changing the power and frequency of the optical input. Tens to hundreds of GHz or even THz of frequency separation can be achieved. Therefore, by taking advantage of such period-one nonlinear dynamics, an optical signal carrying a microwave signal with a frequency from a few tens to hundreds of GHz can be generated all-optically. As also shown in Fig. 1 (right), the spectral components around the regeneration of injection are highly asymmetric in intensity, where the lower-frequency oscillation sideband is 23-dB stronger than the upper-frequency one. Therefore, we could take advantage of this intensity-asymmetry between these sidebands to convert an optical input with DSB features to an optical output with SSB features. As also shown in Fig. 1 (right), the lower-frequency oscillation sideband has a power close to that of the regeneration. Therefore, we apply this characteristic to carry out microwave power amplification.

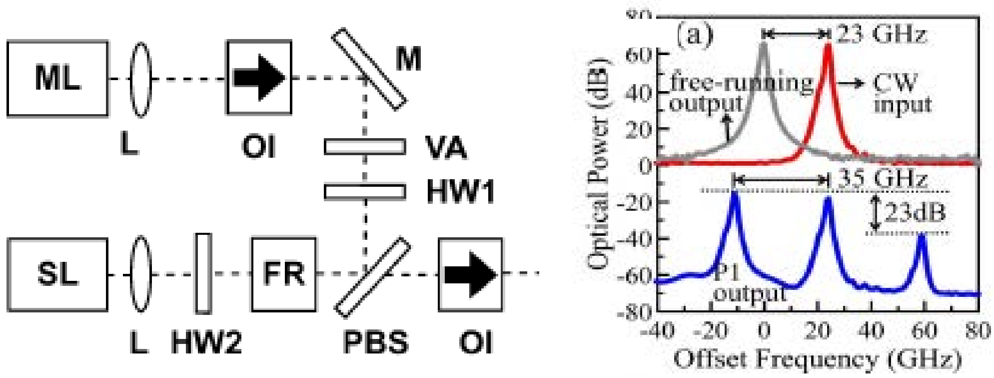

Figure 1: (Left) Schematic of the proposed photonic system. ML: master laser; SL: slave laser; L; lens; PBS: polarizing beam splitter; M: mirror; HW: half-wave plate; FR: Faraday rotator; V: variable attenuator; OI: optical isolator

(Right) Optical spectra of the system output at free-running (gray curve) and P1 dynamics (blue curve), and of the input optical signal (red curve). For clear visibility, the blue curve is down-shifted with respect to the other curves. The x-axis is relative to the free-running frequency of the injected laser.

Results and Achievements

1. *Optical DSB-to-SSB conversion*

Goals: To "photonically" convert optical double-sideband (DSB) modulation signals to optical single-sideband (SSB) modulation signals for operating microwave frequencies from a few tens to hundreds of gigahertz (or even up to terahertz regime) with their microwave features, such as linewidth and phase noise, maintained after conversion.

Results: We have demonstrated that, for operating microwave frequencies up to 40 GHz, our proposed scheme can regenerate the microwave features, such as linewidth and phase noise, of an optical DSB input while converting its optical feature into SSB with an intensity difference of at least 20 dB. The bit-error ratio down to 10^{-9} for a data rate of at least 2.5 Gb/s is feasible with a receiver sensitivity improvement of up to 15 dB. Such conversion is feasible for an operating microwave frequency up to at least 100 GHz, which has not yet been experimentally demonstrated due to the bandwidth limitation of the electronics used in our study, not by our proposed scheme. The proposed system can be self-adapted to certain changes in the operating microwave frequency and can operate stably under certain fluctuations in the input optical power and frequency.

Areas of interest:

(1) broadband (a few to hundreds of Gbit/s) wireless access for commercial and military communication networks, such as the 5th or 6th generation of cellular phone communication networks, which requires microwave carriers ranging from 60 GHz to more than 100 GHz.

(2) Radar and phase-array antenna for commercial, academic, and military purposes, which use optical carriers to deliver microwave signals to remote areas for wireless sensing, imaging, and detection.

Comparisons with other proposed schemes:

(1) Passive optical filtering:
This scheme is basically not frequency-tunable unless an optical filter of a different center frequency or of a different pass-band is used. In addition, no receiver sensitivity improvement is possible. Therefore, our proposed scheme is a lot better (you can say 100 times better or more) in terms of frequency tenability and is more than 40 times better in terms of receiver sensitivity.

(2) Dual-drive Mach–Zehnder modulator:

This scheme is limited to around 40 GHz due to the restriction of the electronic bandwidth. In addition, very high precision of microwave phase is required and very high electrical power is needed. Therefore, our proposed scheme is at least 3 times better in terms of frequency tunability, and is a lot better in terms of system operation and power consumption.

2. ***Photonic microwave generation and stabilization***:

Goals: To "photonically" generate microwaves that are broadly tunable from a few tens to hundreds of gigahertz (or even up to terahertz regime), and, at the same time, that are highly stable with a linewidth down to 1 Hz or even sub-Hz.

Results: Microwave generation that are broadly tunable from 10 GHz to 40 GHz and, at the same time, that are highly stable with a linewidth down to 1 Hz was demonstrated using our proposed scheme based on period-one nonlinear dynamics of semiconductor lasers. The highest demonstrable frequency was limited by the bandwidth of the devices used in our study, not by our proposed scheme. A higher frequency, such as 100 GHz, is feasible, which remains to be demonstrated experimentally.

Areas of interest:

(3) broadband (a few to hundreds of Gbit/s) wireless access for commercial and military communication networks, such as the 5th or 6th generation of cellular phone communication networks, which requires microwave carriers ranging from 60 GHz to more than 100 GHz.

(4) High-speed optical signal processing for optical communication systems, such as optical clock recovery and division, which requires optical signals carrying microwaves ranging from 10 GHz up to more than 100 GHz, even 160 GHz, depending on different system requirements.

(5) Radar and phase-array antenna for commercial, academic, and military purposes, which use optical carriers to deliver microwave signals to remote areas for wireless sensing, imaging, and detection.

Comparisons with other proposed schemes:

(1) Mode-locked semiconductor laser:

This scheme generates microwaves that are tunable only within a few gigahertz and that are stable with a linewidth down to the order of 100 Hz to 1 kHz only. Therefore, our proposed scheme is 10 to 100 times better in terms of frequency

tunability, and is 100 to 1000 times better in terms of microwave linewidth and stability.

(2) Optical heterodyne:
This scheme generates microwaves with features similar to our proposed scheme. However, many strict and challenging operating conditions are required to satisfy using this scheme in order to yield such microwaves, making it complex and difficult to operate and to achieve the purpose.

(3) Optoelectronic oscillator:
This scheme generates microwaves that are tunable only within a few gigahertz and that are stable with a linewidth down to 1 Hz and even sub-Hz. Therefore, our proposed scheme is 10 to 100 times better in terms of frequency tunability, and is similar in terms of microwave linewidth and stability.

3. ***Photonic microwave amplification***:

Goals: To "photonically" amplify microwaves for a broad frequency range, from a few tens to hundreds of gigahertz (or even up to terahertz regime), and for a wide gain range, from a few dB to 20 dB.

Results: Microwave amplification for frequency from 10 GHz to 60 GHz and for gain from 10 dB to 30 dB was demonstrated using our proposed scheme based on period-one nonlinear dynamics of semiconductor lasers. The highest demonstrable frequency was limited by the bandwidth of the devices used in our study, not by our proposed scheme. A higher frequency, such as 100 GHz, is feasible, which remains to be demonstrated experimentally.

Areas of interest:

(1) broadband (a few to hundreds of Gbit/s) wireless access for commercial and military communication networks, such as the 5th or 6th generation of cellular phone communication networks, which requires microwave carriers ranging from 60 GHz to more than 100 GHz.

(2) Radar and phase-array antenna for commercial, academic, and military purposes, which use optical carriers to deliver microwave signals to remote areas for wireless sensing, imaging, and detection.

Comparisons with other proposed schemes:

(3) Passive optical filtering:
This scheme is basically not frequency-tunable and gain-tunable unless an optical filter of a different center frequency or of a different pass-band is used. In

addition, the highest demonstrable gain is only about 9 dB. Therefore, our proposed scheme is a lot better (you can say 100 times better or more) in terms of frequency tunability, and is more than 100 times better in terms of microwave gain.

(4) Brillouin scattering:
This scheme is basically not frequency-tunable and gain-tunable. In addition, the highest demonstrable gain is only about 13 dB. Therefore, our proposed scheme is a lot better (you can say 100 times better or more) in terms of frequency tunability, and is more than 100 times better in terms of microwave gain.

These microwave functionalities are either expensive or difficult, if not impossible, to achieve using traditional electronic approaches if high-frequency, such as V and W bands, applications are of interest. Therefore, our proposed photonic approaches provide promising solutions. The results of our research have been presented in **8 conferences (18 contributed papers**). Moreover, due to our achievements in the study of nonlinear laser dynamics, we have been invited to deliver **3 invited talks at 3 conferences**. In addition, **4 papers have been published in *Optics Express*** and **2 papers in preparation**. A list of publications, awards, grants & projects, and academic services over the past year is presented as follows.

I. Publications

Refereed Journal Papers

1. Y.H. Hung and **S.K. Hwang**, "Photonic microwave stabilization for period-one nonlinear dynamics of semiconductor lasers using optical modulation sideband injection locking", *Optics Express*, Vol. 23, No. 5, pp. 6520-6532 (2015).
2. S.S. Lin, **S.K. Hwang**, and J.M. Liu, "High-power noise-like pulse generation using a 1.56-µm all-fiber laser system", *Optics Express* , Vol. 23, No. 14, pp. 18256-18268 (2015)
3. K.H. Lo, **S.K. Hwang**, and S. Donati, "Optical feedback stabilization of photonic microwave generation using period-one nonlinear dynamics of semiconductor lasers", *Optics Express*, Vol. 22, No. 15, pp. 18648-18661, (2014).
4. S.S. Lin, **S.K. Hwang**, and J.M. Liu, "Supercontinuum generation in highly nonlinear fibers using amplified noise-like optical pulses", *Optics Express*, Vol. 22, No. 4, pp. 4152-4160, (2014).
5. K.L. Hsieh, Y.H. Hung and **S.K. Hwang**, "Radio-over-fiber DSB-to-SSB conversion using semiconductor lasers at stable locking dynamics", in preparation (2015).
6. K.L. Hsieh and **S.K. Hwang**, "Radio-over-fiber microwave amplification using semiconductor lasers at stable locking dynamics", in preparation (2015).

Refereed Conference Papers

Invited Talks

1. **S.K. Hwang** and Y.H. Hung, "Highly stable and broadly tunable photonic microwave generation using period-one nonlinear dynamics of semiconductor lasers", *Proceedings of International Symposium on Nonlinear Theory and Its Applications 2015* (2015) (**Invited Talk**).
2. **S.K. Hwang**, Y.H. Hung, and K.H. Lo, and S. Donati, "High-level dynamics in semiconductor lasers: regimes and applications", *Proceedings of Numerical Simulation of Optoelectronic Devices 2015* (2015). (**Invited Talk**).
3. **S.K. Hwang**, "Nonlinear Dynamics of Semiconductor Lasers for Photonic Microwave Applications", *Proceedings of International Symposium on Physics and Applications of Laser Dynamics 2014 (IS-PALD)* (2014) (**Invited Talk**).

Contributed Talks

1. Y.H. Hung and **S.K. Hwang**, "Tunable narrow-linewidth photonic microwave oscillators using optically injected semiconductor lasers at period-one dynamics", *Proceedings of Progress in Electromagnetics Research Symposium 2015 (PIERS)* (2015).
2. K.H. Lo and **S.K. Hwang**, "Photonic microwave generation and stabilization using semiconductor lasers at period-one dynamics", *Proceedings of Progress in Electromagnetics Research Symposium 2015 (PIERS)* (2015).
3. K.L. Hsieh and **S.K. Hwang**, "Photonic microwave amplification for radio-over-fiber links utilizing semiconductor lasers at stable locking dynamics", *Proceedings of Progress in Electromagnetics Research Symposium 2015 (PIERS)* (2015).
4. Y.H. Hung and **S.K. Hwang**, "Tunable Narrow-Linewidth Photonic Microwave Oscillators Using Optically Injected Semiconductor Lasers at Period-One Dynamics", *Proceedings of Annual Meeting of the Physical Society of Republic of China (2015).*
5. K.H. Lo, **S.K. Hwang** and S. Donati, "Optical feedback stabilization of photonic microwave generation using period-one nonlinear dynamics of semiconductor lasers", *Proceedings of Annual Meeting of the Physical Society of Republic of China (2015).*
6. K.L. Hsieh and **S.K. Hwang**, "Stable locking dynamics of semiconductor lasers for photonic microwave amplification", *Proceedings of Annual Meeting of the Physical Society of Republic of China (2015).*
7. Y.H. Hung and **S.K. Hwang**, "Photonic millimeter-wave frequency multiplication with tunable multiplication factor utilizing period-one dynamics of semiconductor lasers", *Proceedings of 2014 International Topical Meeting on Microwave Photonics (MWP)* (2014).

8. Y.H. Hung and **S.K. Hwang**, “Semiconductor lasers at period-one dynamics for amplification of microwaves in radio-over-fiber links”, *Proceedings of Optoelectronics and Communications Conference 2014 (OECC)* (2014).
9. K.L. Hsieh, Y.H. Hung, and **S.K. Hwang**, “Optical DSB-to-SSB conversion for radio-over-fiber links utilizing semiconductor lasers at stable locking dynamics”, *Proceedings of Optoelectronics and Communications Conference 2014 (OECC)* (2014).
10. K.H. Lo and **S.K. Hwang**, “Linewidth reduction through optical feedback for photonic microwave oscillators using optically injected semiconductor laser dynamics”, *Proceedings of Optoelectronics and Communications Conference 2014 (OECC)* (2014).
11. Y.H. Hung and **S.K. Hwang**, “Multiplication of microwave frequency utilizing period-one dynamics of optically injected semiconductor lasers”, *Proceedings of International Symposium on Physics and Applications of Laser Dynamics 2014 (IS-PALD)* (2014).
12. K.L. Hsieh and **S.K. Hwang**, “Stable locking dynamics of semiconductor lasers for microwave amplification”, *Proceedings of International Symposium on Physics and Applications of Laser Dynamics 2014 (IS-PALD)* (2014).
13. S.S. Lin**, S.K. Hwang**, and J.M. Liu, “Generation of an octave-spanning supercontinuum in highly nonlinear fibers pumped by noise-like pulses”, *Proceedings of International Society for Optical Engineering (SPIE) Optics and Photonics Meeting* (2014).
14. Y.H. Hung and **S.K. Hwang**, “Photonic microwave amplification using period-one nonlinear dynamics of semiconductor lasers”, *Proceedings of Annual Meeting of the Physical Society of Republic of China* (2014).
15. K.L. Hsieh, Y.H. Hung, and **S.K. Hwang**, “Optical DSB-to-SSB conversion using semiconductor lasers at stable locking dynamics”, *Proceedings of Annual Meeting of the Physical Society of Republic of China* (2014).
16. K.H. Lo and **S.K. Hwang**, “Effects of optical feedback on stabilization of microwave generation using period-one nonlinear dynamics of optically injected semiconductor lasers”, *Proceedings of Annual Meeting of the Physical Society of Republic of China* (2014).
17. Y.H. Hung and **S.K. Hwang**, “Tunable narrow-linewidth photonic microwave oscillators using optically injected semiconductor lasers at period-one dynamics”, *Proceedings of Optics and Photonics Taiwan, International Conference 2014 (OPTIC)* (2014).
18. K.L. Hsieh and **S.K. Hwang**, “Stable locking dynamics of semiconductor lasers for photonic microwave amplification in radio-over-fiber links”, *Proceedings of Optics and Photonics Taiwan, International Conference 2014 (OPTIC)* (2014).

II. Awards

1. Award Title: Excellent Teaching Award (National Cheng Kung University)
   Award Winner: **<u>Sheng-Kwang Hwang</u>**

2. Award Title: Best Master Thesis Award (2014 IEEE Tainan Section)
   Award Winner: Kun-Lin Hsieh
   Thesis Advisor: **<u>Sheng-Kwang Hwang</u>**
   Thesis Title: Optical DSB-to-SSB conversion and photonic microwave amplification using stable locking dynamics of semiconductor lasers for radio-over-fiber links

III. Grants & Projects

1. Project Title: Study of exotic nonlinear dynamics using photonically perturbed semiconductor lasers
   Funding Agent: Ministry of Science and Technology, Taiwan
   Contract No.: MOST 103-2112-M-006-013-MY3
   Fund: NT$ 3,881,000
   Project Goal:

   There exist several nonlinear dynamical states, including rogue wave, breather state, and chimera state, which have been just identified or poorly understood. Even compared with chaos, these nonlinear dynamical states manifest themselves as exotic, singular, and complicated in terms of their time evolutions, spectral features, and spatial patterns. There remain various fundamental and important issues to be investigated before gaining sufficiently enough understanding of these exotic nonlinear dynamical states, which include phenomenon definitions, key signatures, formation processes, generation conditions, perturbation effects, and underlying mechanisms. Therefore, our main purpose in this project is to study such issues of these exotic nonlinear dynamical states in depth and breadth through photonically perturbed semiconductor lasers. Understandings of these exotic dynamical states would enable us to gain capability of controlling nonlinear systems for their generation, suppression, and even detection, either the time or the strength of their appearance, which shall lead to technological applications of these dynamical states. For example, the ability of generating rogue waves makes it possible to design photonic systems to excite ultrafast optical pulses with extremely high peak power that is not available at the present moment for the generation of ultrabroad supercontinua and for the study of atomic physics.

2. Project Title: Physical characteristics, bifurcation signatures, underlying mechanisms, and novel applications of nonlinear dynamics in optically injected semiconductor lasers under optical feedback perturbation

Funding Agent: National Science Council, Taiwan

Contract No.: NSC 102-2112-M-006-004

Fund: NT$ 1,121,000

Project Goal:

With increased degrees of freedom, the complex dynamical characteristics of a perturbed laser can be greatly enriched yet more efficiently controlled with the help of another perturbation. Because the interaction between the perturbations and the laser is highly complex and nonlinear, it is not intuitive and straightforward to expect in advance that a perturbed laser would be more stable or more unstable when simultaneously subject to another perturbation of different levels. This opens up an opportunity to generate a greater variety of different dynamical states with greater differences (or improvements) in temporal and spectral characteristics by using a laser subject to two different perturbations concurrently instead of one. Therefore, our purpose in this project is to study the physical characteristics and the underlying mechanisms of nonlinear dynamics in a semiconductor laser subject simultaneously to two different perturbations, namely, optical injection and optical feedback. These understandings shall provide implications of how such a laser system can be utilized for novel photonics applications. For example, by applying both optical injection and optical feedback perturbations to a semiconductor laser, highly stable (a linewidth of tens of kHz) and broadly tunable (from a few to tens of gigahertz) microwave generation is highly expected, which is critical in various applications, such as broadband wireless access, high-speed signal processing, and radar and antenna.

3. Project Title: Nonlinear dynamics of photonics for optical signal processing – optical frequency conversion and optical DSB-to-SSB conversion

Funding Agent: Asian Office of Aerospace Research and Development, U.S. Air Force

Grant No.: FA2386-14-1-0006

Fund: US$ 25,000

4. Project Title: Nonlinear Photonic Systems for V- and W-Band Antenna Remoting Applications – Microwave Generation and Microwave Amplification

Funding Agent: Asian Office of Aerospace Research and Development, U.S. Air Force

Grant No.: FA2386-15-1-4026
Fund: US$ 25,000